Freshwater Aquatic Nuisance Species Impacts and Management Costs and Benefits at Federal Water Resources Projects[1]

by Richard A. Cole

THE ISSUE: A small fraction of the species that inhabit the nation's fresh waters become aquatic nuisance species (ANS) when they significantly degrade services provided by water resources. Government agencies, utilities, and other water resource managers incur substantial costs controlling ANS and repairing damage to restore service performance to desired levels. National costs of and benefits from ANS management appear to be increasing, but neither is particularly well documented (e.g., Lovell and Stone (2005)). Meanwhile, competition for federal funding continues to grow and to require ever stronger evidence of net benefit from management measures in order to justify program budgets in the annual ANS management cycle (Figure 1).

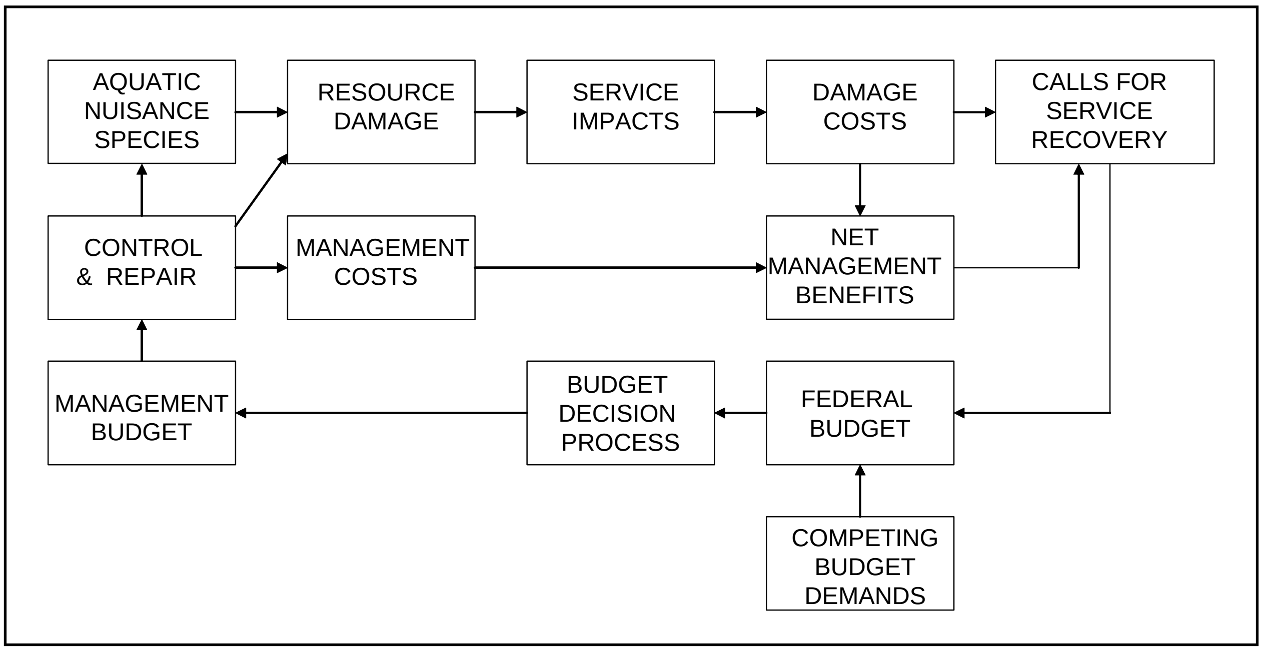

Figure 1. Annual management cycle for ANS impacts

This technical note inventories the state of ANS information pertaining to resource damage, service impact, public calls for service recovery, and the costs of and net benefits from damage management. It follows the ANS budget and management cycle described in Figure 1, starting with identification of ANS through the damages they cause to resources and services, calls for recovery of lost service benefits, ANS management, management actions, and ends with the net benefits gained from those types of management, as well as the contribution of information to the next round of annual budget decisions. In the cycle, the public first recognizes damage costs and calls for

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Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
SEP 2006	**N/A**	**-**

4. TITLE AND SUBTITLE	
Freshwater Aquatic Nuisance Species Impacts and Management Costs and Benefits at Federal Water Resources Projects	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Engineer Research and Development Center Vicksburg, MS 39180**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**14**	

management funding. Then, based on the net benefits from management (gross benefit recovery minus management costs), and remaining damage costs, the management budget is reevaluated by decision makers in the context of competing demands for budget funding.

This technical note briefly describes the process, including how freshwater ANS are identified, what resources and services are commonly damaged, and the types of control and repair measures that may be taken. Existing information on management costs, damage costs, and net benefits gained from management is summarized. Finally, a short summary is given of implications for project operations and maintenance by the Corps of Engineers.

IDENTIFYING ANS: Species attain nuisance status when and/or where the costs they impose on society significantly exceed the human benefits derived from any services they may provide. The ANS of freshwater reservoirs and waterways reduce operations efficiencies at power and water supply, navigation, and flood damage reduction projects; decrease water potability; diminish recreational opportunities; and degrade ecosystem functions that help maintain human health and help sustain biodiversity and species threatened with extinction. ANS are sometimes incorrectly associated solely with nonnative invasive species. But nuisance status may be assigned species in their native habitats as well as in newly colonized habitat where they have been introduced or have naturally invaded. Nuisance status is typically associated with a sharp increase in population abundance, but that alone is not enough to identify ANS. A nuisance results when the service benefits of a species are exceeded by other service degradation.

For example, a native species valued as forage for a game fish in its native habitat becomes a nuisance in new habitats where it contributes significantly to the decline of native species. The red shiner (*Cyprinella lutrensis*) is a good example. Endemic to the Mississippi drainage, it has been introduced into rivers of the southwestern United States where it endangers other species (e.g., Fuller et al. (1999)). But ANS can be identified among species in their native habitat as well. For many years, state fish and game agencies removed native “rough fish” from natural streams and lakes because they competed with game fish, some of which were introduced species. Some state agencies continue this practice in reservoirs.

Nuisance status can change quickly as economic and ecological settings change. Nuisance outbreaks occur more commonly where ecological processes are destabilized by environmental changes, such as eutrophication, or decreased predation. Aquatic plants and algae are more likely to reach nuisance levels when the habitat is enriched with fine sediment and nutrients. Because the sources of enrichment often are difficult to control, more expedient measures are taken to control algae and plants when the need is pressing. Animal populations are more likely to reach nuisance levels when predators and parasites are absent or fail to control them. Managers of non-native nuisance species often seek reestablishment of an ecological “equilibrium” by purposeful introduction of predators and parasites.

The alewife (*Alosa pseudoherengus*) is a case in point. It invaded the upper Great Lakes from the east coast of the United States through the Welland canal, which was built to circumvent Niagara Falls. Once there, it probably contributed to the decline of native whitefish species (*Coregonus* spp.) and definitely sullied lake shorelines with millions of rotting carcasses following massive die-offs (Fuller et al. 1999). Alewife populations soared in the upper Great Lakes because native predators

had been decimated by overfishing and by sea lamprey predation (another invasive species from the east coast). Nuisance die-offs decreased sharply and surviving native whitefish populations equilibrated after west-coast salmon (*Onchorhyncus* spp.) were successfully introduced into the upper Great Lakes to control the alewife fluctuations while establishing a valued sportfishery. Alewife status changed from nuisance to beneficial as it became key to sustaining the highly regarded salmon fishery in the upper Great Lakes.

Destabilizing disturbances can be natural as well as human caused, and can result from complex interactions between human endeavor and natural process. In some environments, climate variations over the past 20,000 years interacted with topography to cause extreme and somewhat isolated conditions that decimated native communities and slowed natural colonization by new species. Their biotic communities characteristically exhibit low native biodiversity as a consequence. The Great Lakes comprise one example, as do freshwater habitats of south Florida and the western United States. Low native biodiversity makes these areas especially suitable for successful species invasion, once barriers are circumvented (e.g., the Erie and Welland Canals around Niagara Falls), and, with it, further transformation of ecosystem structure and function. By 1991, at least 136 nonnative species had become established in the Great Lakes (Mills et al. 1991) and several more have been more recently recognized (e.g., Lovell and Stone (2005)).

Waterway and reservoir development also transforms original river habitat, which often depresses native biodiversity and sets the stage for successful species invasion, especially when accompanied by widespread alteration of watersheds. ANS management is, therefore, part of the cost of doing business in landscapes and waterways dominated by human development and use.

RESOURCE DAMAGE AND SERVICE IMPACTS: The water resource and service impacts caused by ANS take numerous forms including altered capacity for navigation, flood mitigation, power generation, recreation, water supply to domestic and industrial users, and ecosystem function that sustains good human health and species viability. The physical, chemical, and biological impacts of different nuisance species in different settings vary greatly in form and degree of economic and environmental impact. Similar impacts on resources and services set in different geographical locations often result in different impacts on economic benefits depending on the demand for service. Even extreme resource impacts may affect public benefits little where the demand for service is negligible. Dense growths of aquatic plants at a reservoir, for example, may impact recreational service without reducing net benefits significantly because there is little unsatisfied demand for recreation at that site.

One of the more widespread resource problems in reservoirs holding public water supply for domestic use is degradation of water quality by native species of pelagic and benthic algae. These algae are geographically widely distributed species that periodically form nuisance blooms following phosphorus and other nutrient enrichment associated with altered watershed conditions and sewage plant and livestock feedlot discharge. Fouled beaches, plugged water intakes, and objectionable odor and taste of the water supply are typical consequences. A common nuisance species is the filamentous green algae, *Cladophora* spp, which attaches to hard bottom structures in shallow, clear waters. Some pelagic cyanobacteria (blue-green algae) produce toxic chemicals harmful to other species, including, in extreme cases, those livestock and pets that drink the water, and humans (Falconer 1999). Consistently high abundances of algae contribute to severe oxygen depletion and

other systemic effects that may reduce the quality of sportfisheries, swimming, and other recreational use.

Recreational opportunities are also impacted by dense growths of rooted aquatic plants, which most typically occur in nuisance proportions in clear shallow waters where fine, nutrient-enriched sediments have accumulated. Dense growths of rooted submergent plants can impede swimming, boating, and sportfishing. However, net impact assessment is often complicated by the fact that some services may improve as others decrease in response to invasion of non-native species or changes in native species abundance. Henderson and Kirk (2002), for example, showed that anglers responded positively to aquatic plants at the two sites they studied.

Some native rooted submergent plants grow to nuisance status, but a few alien species are often involved. Four of the most widespread—hydrilla, Asian watermilfoil, Brazilian elodea, and curly leaf pondweed—are especially invasive. Dead plants sometimes accumulate and rot on shore where they may reduce recreational benefits and property values. Drinking water quality may be affected. Some dense growths are natural, but human-caused sediment and nutrient enrichment often are underlying causes for nuisance growth. Important freshwater ANS are listed in Table 1.

Other nuisance plants float on the surface where they may impede some commercial activity but are more likely to interfere with recreational boating, fishing, and swimming. They can contribute to species endangerment by causing severe hypoxia and light depression in subsurface waters. The water hyacinth may be the best known, but several other alien species now contribute to the problem. Another group of aquatic plants is comprised of emergent species that root in wetlands where they out-compete desired native species for space and nutrients, exemplified by purple loosestrife and common reed. Purple loosestrife often replaces wetland plants of higher livestock forage value, but also may threaten some imperiled species, such as the bog turtle (*Clemmys muhlenbergi*).

Table 1
Important Freshwater ANS

Species	Name
Bluegreen Algae (Cyanobacteria)	*Aphanizomenon* spp *Anabaena* spp *Microcystis* spp *Cylindrospermopsis raciborskii* *Lyngbya wollei*
Green Algae	*Cladophora* spp Hydrodictyon spp
Vascular Plants	curly-leaf pondweed (*Potomogeton crispus*) Asian watermilfoil (*Myriophyllum spicatum*) hydrilla (*Hydrilla verticillata*) Brazilian elodea (*Egeria densa*) water hyacinth (*Eichornia crassipes*) purple loosestrife (*Lythrium salicaria*) common reed (*Phragmites australis*)
Animals	sea lamprey (*Petromyzon marinus*) common carp (*Cyprinus carpio*) largemouth bass (*Micropterus salmoides*) Asian clam (*Corbicula fluminea*) zebra mussel (*Dreissena polymorpha*)

The common carp is the most widespread fish species often considered a nuisance, but is increasingly viewed as beneficial in settings where it contributes to both recreational and commercial fisheries (Cooper 1987, Fuller et al. 1999). Exactly when common carp were first introduced to waters in the United States is uncertain, but they did not become widespread until after the U.S. Fish Commission began importing them in 1877 for widespread distribution and stocking to satisfy demands for what was then a popular food fish (Fuller et al. 1999). Once well established, human preferences changed and many millions of dollars were spent on carp control by state agencies and private groups who believed that carp interfered with the reproduction and survival of more desirable food and game species by increasing water turbidity and destroying vegetation. Investments in control by trapping, barriers, and predator management continue in specific locations,

but have waned overall in the absence of long-term effectiveness. Carp are now believed to be established in all states except Alaska and Maine. They have gained in sportfishing popularity (Cooper 1987), which is also a cost-effective form of control.

Otherwise highly regarded native game species become nuisance species wherever they threaten native species with extinction. This impact is especially widespread in waters of the western United States, where nonnative species of the sunfish (Centrarchidae) and trout (Salmonidae) families have been introduced in virtually all major rivers and reservoirs as well as in many small ponds and springs. The largemouth bass is among those species most widely introduced into new habitats in the United States and worldwide, and is among fish species often implicated with endangerment or extinction of native species. Its introduction into the western United States has been connected with local elimination of several native minnows and pupfish, frogs and salamanders (Fuller et al. 1999). Rainbow trout (*Oncorhynchus mykiss*), brook trout (*Salvelinus fontinalis*), and brown trout (*Salmo trutta*) have been widely introduced on top of native salmonid species and subspecies where they have contributed to the endangerment of some and the extinction of at least one (Fuller et al. 1999).

The bullfrog (*Rana catesbeiana*) is the sole native amphibian that is commonly considered a nuisance species, mostly in the western United States, where it has been widely introduced. A valued food and recreation species of keystone ecological importance in native environments, in the numerous locations where it has been introduced, the bullfrog is a voracious predator and competitor that threatens some smaller native amphibians with extinction. A nonnative species, the marine toad (*Bufo marinus*) is limited to Florida and south Texas where it is a nuisance mostly for pet owners. Toxic skin secretions can be lethal to cats and dogs and other mammals.

Other fish species have become a more local nuisance problem, although sometimes of immense regional impact. The Great Lakes is one such region, which has had a long history of invasion by fish species, including the alewife and sea lamprey. The Corps of Engineers participates in an international sea lamprey control program, which includes construction and maintenance of lamprey traps and application of lampricide. A number of other fish species have invaded the Great Lakes more recently, including the white perch (*Morone americana*), round goby (*Neogobius melanostomus*) and the ruffe (*Gymnocephalus cernuus*). The latter two species are Eurasian natives that probably were transported in ship ballast water from the Baltic region. A native of the Atlantic Coast, the white perch followed the alewife and the lamprey into the upper Great Lakes by way of the Erie and Welland canals.

Florida has also been exceptionally exposed to waves of alien plant (Schmitz et al. 1991) and fish invasions. Shafland (2003) listed 22 species of nonnative fish that have established populations in southern Florida from origins all over the world (Figure 2). Some were established by fish that escaped from tropical fish farms or were released pets. Others were released to establish food or recreational fisheries. Many are limited to Florida by their intolerance of low water temperatures, and have not become significant nuisances to date. Their impacts are largely undocumented (Fuller et al. 1999), but there is concern about potential impacts (e.g., Hoover et al. 2004) and more specifically about invasions of Everglades National Park by some species. Some of the more locally

Figure 2. A growing list of ANS have made their way from Caspian Sea tributaries to the Great Lakes by way of canals connecting to Baltic tributaries and ship ballast water taken from Baltic harbors. Florida's invasive species are predominantly from tropical South America, but include species from other origins. Many native ANS have moved westward from the eastern United States through canals and, much more commonly, through human introduction. An exception, the rainbow trout, has been introduced from west coast origins both eastward and worldwide.

widespread include the sailfin catfish (*Pterygoplichthys multiradiatus* and brown hoplo (*Hoplosternum littorale*) from South America, and the walking catfish (*Clarias batrachus),* bullseye snakehead *Channa marulius,* and swamp eel (*Monopterus albus*) from eastern Asia. Several species in the cichlid family are regarded as nuisances because of their threats to native species, including the spotted tilapia *(Tilapia mariae*) and blue tilapia (*Oreochromis aureus)* from Africa, and the Mayan cichlid (*Cichlasoma urophthalmus*) and black acara (*Cichlasoma bimaculatum*) from tropical America. A large predator of the same family, the butterfly peacock bass (*Cichla ocellaris*), was introduced to southeastern Florida from South America to control other cichlid species and to provide highly regarded sportfishing.

Biting insects are the archetypical nuisance species. All have aquatic life stages and most are native species in the fly order Diptera. Some are alien species, such as mosquito species associated with the establishment of West Nile virus in the United States. Millions of dollars are annually spent on mosquito control alone. But many other aquatic insect species are bothersome at times. Black flies (Simuliidae), no-see-ums (Ceraptopogonidae), horseflies and deerflies (Tabanidae) often drive people from their fishing, swimming, boating, and other outdoor activities. In fewer places than historically, because of widespread pollutants, the bodies of burrowing mayflies accumulate locally on roads where they can become slick enough to cause traffic accidents.

A few leech species are among the non-insect biting invertebrates that occasionally rise to local nuisance status for swimmers. Some snail species are vectors for a microscopic invertebrate that is

the cause of swimmer's itch. And of course some invertebrates can cause serious human diseases, such as parasitic worms and microscopic sporozoans including species in the genera *Plasmodium* (malaria), *Cryptosporidium*, and *Giardia*. Whirling disease, caused by *Myxobolus cerebralis*, a sporozoan parasite accidentally introduced from Eurasia, devastates trout populations and the fisheries that depend on them.

Other invertebrates are more likely to have ecological impacts that alter abundances of recreationally important species or species threatened with extinction. The zebra mussel moved rapidly into the Mississippi River system from Lake St. Clair where it first became established in the United States after accidental introduction from Europe in ship ballast water. While it has contributed to increased water clarity by filtering out particulate organic matter, it causes major changes in food webs and, possibly, the distribution of contaminants (DePinto and Narayanan 1997); drives up costs of maintaining water intakes, pumps, gauges, boat hulls, and other structures; and threatens some native mussel species (Schloesser et al. 1996). Two Eurasian crustacean species introduced to the Great Lakes by way of ship ballast water (the fishhook waterflea, *Cercopagis pengoi*, and the spiny waterflea, *Bythotrephes cederstroemi*) have caused changes in food chains that reduce abundances of native zooplankton species (e.g., Ricciardi and MacIsaac (2000)), but their damage costs, if any, have yet to be quantified.

Water resources development has facilitated establishment and spread of nuisance freshwater species by creating supportive habitat and avenues for their dispersal into new habitats. Many nuisance species have either flourished in or spread through canals, lock and dam structures, reservoirs, and developed harbors. In other situations, dams and other engineered structures can act as barriers to dispersal. Operators of water resources projects are often in key positions for inspecting for, preventing movement of, controlling, and mitigating damage caused by nuisance species.

MANAGING ANS DAMAGES: ANS damages are managed by controlling ANS abundance and by repairing damaged structures, both natural and engineered. Ultimately, the most effective approach to nuisance management is to address the underlying causes of ecosystem imbalance, where feasible, and to reduce the unauthorized introductions of nonnative species. These strategies are complex and expensive, however, and have as yet to be fully adopted, leaving affected parties to deal locally with nuisance species as best they can. Regional and national cost estimates are of interest in part to evaluate a more strategic approach to nuisance species management. The quality of information available at each perceived impact site is also relevant because of the cumulative effect of project management decisions on national program effectiveness.

Because beneficial waterways and reservoirs may establish chronic conditions favoring nuisance species, a variety of chemical, physical, and biological treatments are used to control nuisance-level abundances to maintain services and benefits. They vary in effectiveness depending on the species and the environmental context. Development of new and refined techniques for management and control is the primary focus of research on ANS.

Chemical treatments include a large variety of pesticides for plants and animals that have to be applied to the water or the atmosphere (insect spray), or painted on surfaces to prevent attachment (e.g., invasive byssate mussels), or to neutralize noxious water tastes, odors, and toxic compounds. Chemical treatments have cost advantages, but often have undesirable systemic effects on species

other than the targeted species. For example, the chemical used to control sea lampreys has reduced their impact by 90 percent, but also harms some other species (Fuller et al. 1999). As a consequence, other approaches are being incorporated into the program, including barriers and male lamprey sterilization.

Physical-mechanical treatments include cutting, scraping, filtering, scouring, netting, trapping, and barricading against nuisance species—including various hydraulic, dredging, thermal, electrical, shading, and aeration techniques designed to prevent invasion or growth. They usually have less side effect than chemicals, but often cost more because of labor needs. Aquatic plants are often cut and harvested using specially designed vessels (Madsen 2000). Mollusks are scraped from boat hulls and, less often, from intake structures. Where a source of heat is available, such as in power plant cooling systems, increasing temperature to intolerable levels might be used to remove encrustations of clams (Tippit and Miller 1993). Fish are removed with nets and traps, or are blocked by weirs and curtains of fabric or air bubbles, and electrical fields (e.g., Murphy and Willis (1996)). Less frequently, nutrient-loaded water may be diverted from lakes to slow nutrient enrichment (Cooke et al. 1993), or the lakes may be mixed via aeration to remove nutrients through oxidation/precipitation (Cooke et al. 1993). More commonly, a sequence of physical filtration, sedimentation, flocculation and chemical treatments is used in water treatment plants to remove suspensions (algae and detritus), odors, tastes, and toxins caused by eutrophication.

Self-regenerating biological controls are sought to reduce maintenance costs. However, some unintended outcomes have made the introduction of nonnative species for biocontrol purposes a worrisome choice. They work best when the biocontrol agent is a narrowly adapted (host-specific) predator, parasite, or pathogen, and possible undesirable impacts are carefully considered (e.g., Cofrancesco (1998)). Good examples include the beetle species introduced to control water hyacinth and alligatorweed (*Alternanthera philoxeroides*), as they do in their native South American habitats (Charudattan 1986, Coulson 1977).

The care directed at selection of biocontrol agents stems in part from some becoming costly nuisance species. The western mosquito fish (*Gambusia affinis*) has been introduced widely to control mosquitoes and, in the process, has contributed to the extinction of two fish species and the endangerment of several others (Miller et al. 1989, Fuller et al. 1999). The grass carp (*Ctenopharyngodon idella*) is an Asian species that was purposefully introduced to control nuisance plant growths, starting in 1963, but has since spread to other ecosystems where it can negatively impact aquatic plants and invertebrate foods that provide beneficial habitat for desired species (Fuller et al. 1999). Stocking the species is now entirely prohibited in some states, while in other states only certified triploid individuals, which are typically sterile, are permitted.

Two other biocontrol agents now threaten aquatic resources enough to require costly control. The bighead carp (*Hypophthalmichthys nobilis*) and silver carp (*Hypophthalmichthys molitrix*) are recent introductions that escaped from aquacultural ponds where they were stocked to improve water quality by reducing plankton concentrations. They have become established in the Mississippi drainage and are approaching the Chicago Sanitary and Ship Canal, which connects Lake Michigan to the Mississippi drainage. Their impact in the Great Lakes is feared among other reasons because they might displace planktivorous fish that would provide better forage for the highly valued

salmonid fishery in the Great Lakes. In 2002, the Corps of Engineers completed an electrical barrier to movement of fish both out of and into the Great Lakes.

Damage caused by large plants and animals is typically mitigated by controlling species abundance at the impact site. Algal blooms may also be controlled through physical and chemical techniques that decrease nutrient concentration, such as by artificial mixing and application of alum (Cooke et al. 1993). This approach to algal control is sometimes used to alter natural ecosystem functions in support of lake sportfishing and other recreational use. The quality of drinking water degraded by algae is more typically improved at water treatment plants, which use a combination of physical (e.g., sand filters) and chemical techniques (e.g., chlorination, detoxification) to repair the damage.

MANAGEMENT COSTS: Management costs are conceptually easier to assess than the value of lost benefits, but require complete and accurate records for all labor, equipment, supplies, and other costs specifically associated with ANS control and damage repair. Such costs are most commonly identified in programmatic budget categories created for treatment of recurrent problems. More specifically, ANS management costs often are difficult to separate from other project management costs. The typical programmatic summary of management costs lacks the detail necessary to analyze management effectiveness site by site, and therefore limit the information needed by decision makers to improve management efficiency.

In a recent review, Lovell and Stone (2005) concluded that: “The cost of preventing and controlling invasive species is not well understood or documented, but estimates indicate that the costs are quite high, in the range of millions to billions of dollars per year.” In large part because expenditure monitoring is insufficiently detailed and consistent across organizations and regions, past estimates of nuisance species management costs were typically fragmented, typically site- and agency-specific, and opportunistic rather than systematically comprehensive. A more systematic approach is needed to develop a consistent method to estimate national costs (Lovell and Stone 2005).

The Office of Technology Assessment (OTA) (1993) estimated the national costs of managing plant ANS to be about $100 million per year in 1991. Of that, about $14.5 million was spent on *Hydrilla* control in Florida alone. Rockwell (2003), however, estimated that Florida spent a total of $25 million yearly over a decade later. Pimental et al. (2000) estimated that the annual management costs for purple loosestrife in the United States approached $45 million.

National management costs for the sum of all animal ANS do not appear to have been estimated. Much of that cost is likely to be associated with a few high profile species, however, which have been studied with mixed results. O’Neil (1997) estimated that management of zebra mussel impacts cost $17.8 million/year in 1995. Park and Hushak (1999) estimated a somewhat higher cost of $30 million per year from 1992 to 1994. About $13 million was spent in the year 2000 on lamprey control and monitoring by Canada and the United States combined (Jenkins 2001) with about two thirds contributed by the United States. Costs of managing ruffe were estimated by Leigh (1998) to be under $1 million per year. Thus management costs borne by the United States for animal ANS in the Great Lakes probably exceeded $28 to $39 million per year in the 1990s by some unknown amount, but probably does not reach the estimated $100 million spent on plant ANS.

Breaking out expenditures by source is also difficult. According to the Government Accounting Office (GAO) (2000), for example, the federal government budgeted $20.4 million for management of invasive fish and aquatic invertebrates, of which the U.S. Coast Guard spent $4.5 million for invasive species control in ship ballast water, and the U.S. Geological Survey spent about $5.5 million on invasive species research. This leaves about $10 million for other activities (lamprey costs alone were about $9 million per year), amounting to about one third to one fourth of the estimated U.S. expenditure on zebra mussel and lamprey impacts. The difference may indicate that the relative fraction of state and private spending is high or that the GAO estimate for federal expenditure on ANS is low.

The costs of managing ANS for environmental benefits, such as for protection and recovery of threatened and endangered species, are impossible to estimate from existing information. Management of sea lamprey and ruffe for food and recreational fishery benefits probably has an additional positive environmental impact on native biodiversity. The dimensions of that impact are unreported, however, if known. On the other hand, the management of nuisance clams is usually site-focused at water intakes, boat hulls, and other engineered structures, and has little effect on natural habitats and species that may be endangered by the alien clams. While the zebra mussel has contributed to the great concern for the continued viability of native freshwater mussels, there has been little quantification of its environmental impact. This appears to be generally true for most other ANS impacts on species vulnerable to extinction.

RESOURCE DAMAGE COSTS: The damages caused by nuisance species are the benefits foregone (or opportunity costs incurred) as a consequence of degraded resources and desired services. Some impacts can be measured in dollars of damage done. Other impacts have no widely accepted economic measure, such as impacts that threaten and endanger species. These environmental impacts are typically measured in non-monetary units of some kind, such as species relative abundance. Lost benefits can include increased costs of barge-shipped goods, flood damages, electricity, water-based recreation, domestic water, and industrial goods dependent on water supply. They may also include the decreased value of property adjacent to projects and the decreased viability of species and the biotic communities they comprise. The record of damage assessments is spotty, however, and national estimates are approximate (Lovell and Stone 2005).

The national damage costs caused by all aquatic and terrestrial nuisance species have been estimated in two studies (OTA 1993, Pimentel et al. 2000), which required broad assumptions about accuracy and representation. OTA (1993) estimated that the total cumulative cost to the nation associated with damages from all terrestrial and aquatic species spanning the years from 1906 though 1991 was $97 to $137 billion. This included damages associated with agriculture, forestry, water resources development, fisheries, utilities, buildings, and natural areas. Pimentel et al. (2000) estimated total damages from the sum of all 6,000 estimated harmful species in the United States to be substantially larger, amounting to about $138 billion per year. Because some important effects cannot be acceptably measured in economic terms, any dollar estimate of national damage costs caused by ANS will fall short of the total cost.

For aquatic ANS, OTA (1993) estimated that about $1.6 billion in cumulative damages had been caused by the three most harmful fish species and the three most harmful aquatic invertebrates. Pimentel (2001) estimated that the United States annually lost at least $1 billion in damages from

introduced fish and $1.3 billion from mollusks. OTA (1993) estimated that the Asian clam alone caused $1 billion per year in damages during the early 1990s (OTA 1993). Estimates of the mean annual damages caused by zebra mussels ranged between $0.3 billion (Cataldo 2001) and $0.5 billion (Sun 1994, Jenkins 2001) during the 1990s. While the sum for these few species is a low estimate of total animal ANS damage value, it may comprise a significant fraction of the total.

The environmental costs of aquatic nuisance species are even less well quantified than the economic costs. ANS have played a role in a large fraction of the fish extinctions that have occurred (Miller et al. 1987), however, and are often identified among the threats to various aquatic species (Williams et al. 1989). Many imperiled species are threatened by a complex mix of environmental changes, including ANS, which are difficult to separate into categories of relative importance.

NET BENEFITS FROM ANS MANAGEMENT: Damage costs are sometimes used to indicate management benefits, but the net benefits derived from ANS management are lower, sometimes substantially so. Complete avoidance or repair of damaged resources and services is rarely possible, and management costs, which must be deducted to determine net benefits, can be high.

Relatively few studies of net benefits from ANS management have been published. Most have been completed for the fisheries of the Great Lakes. Sturtevant and Cangelosi (2000) estimated the net benefits from lamprey control to be about $ 0.5 billion. Jenkins (2001), Hushak (1996), and Leigh (1998) estimated another $0.5 to 0.6 billion in annual ruffe management benefits. However, many of these benefits derive from the same sportfishery protection. Even so, the estimated benefit-cost ratio approaches 50 to 1.

Rockwell (2003) updated analyses completed by Thunberg et al. (1992) and Thunberg and Pearson (1993a, 1993b) and estimated the benefits derived by Florida property owners from flood damage reduction to home owners and improved drainage of citrus and vegetable production, which summed to about $300 million. He also reviewed the literature for estimates of management costs for and recreational benefit from aquatic plant control based on willingness to pay. Then, based on an estimated benefit-cost ratio of 10 to 1, and estimates for the fraction that Florida spent out of the total national expense, he estimated a national benefit of from $1 to $10 billion annually for aquatic plant management.

IMPLICATION FOR CORPS CIVIL WORKS: Recent analyses by Rockwell (2003) and Lovell and Stone (2005) emphasize the shortage of information necessary for accurate estimates of national net benefits from managing ANS. There is, however, little doubt that substantial damage is done to water resources and the services they support, and that management costs are justified in two of the better-studied regions—the Great Lakes and Florida. Knowledge about ANS management effectiveness decreases rapidly as the geographic focus moves away those two regions and expands to national scale.

Researchers working for the Corps of Engineers have contributed significantly to what progress has been made in benefits assessment. The Corps has maintained an Aquatic Plant Control Research Program for many years and more recently started an Aquatic Nuisance Species Research Program at its Engineer Research and Development Center in Vicksburg, MS (U.S. Army Engineer Research and Development Center 2003a, 2003b).

While there have been many technical advances for ANS management, precise quantitative information for most aspects of the resource management cycle shown in Figure 1 remains scarce and fragmented, and is presented in ways that impede integration nationally. Confident assessment of public benefits from ANS management requires a more systematic regional and national approach to cost and benefit assessment, including the costs and benefits of Corps management activities.

The only explicit identification of operations expenditures for ANS management in Corps of Engineers annual reports to the public are for funds allocated and spent to control aquatic nuisance plants in waterways (e.g., U.S. Department of the Army (2004)). In 2003, the Corps Civil Works program reported about $5 million in aquatic plant control costs (USACE 2004). Over 77 percent of that cost accrued in Florida, where water hyacinth and hydrilla are common nuisances.

Presently, there is no published estimate of total ANS management costs administered by the Corps of Engineers nor is there an estimate of the total benefits returned by that management. A Corps-sponsored study is now underway to inventory the existing state of information about ANS impacts at projects managed by the Corps and to make recommendations on how to proceed with future evaluation of costs and benefits of ANS management.

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